NISTIR 6498

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SEM Performance Measurement System, Part 1

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NATIONAL INSTITUTE OF STANDARDS
AND TECHNOLOGY
Raymond G. Kammer, Director

Abstract

This report describes the current design of a system for monitoring the performance of several major subsystems of a scanning electron microscope (SEM). The following subsystems and the associated functional parameters will be monitored. 1) Vacuum system with pressure as a function of time being recorded for the electron-optical column (gun chamber), the specimen chamber, and the sample-loading unit. 2) Several components of the wafer handling system will be timed. 3) The electron gun emission currents and other signals to monitor focal properties of the condenser and objective lenses may be used to correlate with image quality. Experiments are described for tests involving diagnosis of the vacuum system.

Introduction

In semiconductor and other high-tech fabrication processes scanning electron microscopes (SEMs) are used extensively for in-process measurement of the features of wafers that are being manufactured. It is crucial to detect and correct any processing variations on these wafers in early stages of the process without creating excess scrap wafers. In a typical semiconductor fabrication facility, many SEMs (sometimes different makes and types) are used for on-line inspection. Therefore, fast, accurate and uniform operation of SEMs across the fabrication facility (with minimum down time) are some of the main challenges that must be addressed.

This is the first report of activities under the Manufacturing Engineering Laboratory (MEL) Exploratory Project entitled "Development of a Standardized Universal Supervisory Instrument Control System for Metrology Instrumentation". This project is a joint effort between the Automated Production Technology Division (APTD) and Precision Engineering Division (PED). It was formed to explore the feasibility of development of a standardized “universal” supervisory system to monitor functional characteristics of SEMs and other tools to assure continuous, consistent and reliable measurements. Specific questions to identify the feasibility are: 1) can a minimum set of “vital signs” be identified and used to monitor, diagnose and compare the performance of SEMs, 2) can a generic system be implemented to achieve the above mentioned goal. Such a system should have a capability to expand to include other sensing and analysis tools to fulfill future requirements. If feasible, such a system can also be used to maximize the availability of the SEM. This can be done by implementing predictive maintenance using data obtained during the operation of the SEM. Furthermore, this type of system would be applied to other metrology systems such as scanning probe microscopes (SPM) and optical metrology instruments.

A typical SEM used in semiconductor fabrication facilities has several modules/components: electron beam column, optical microscope, wafer handling system, high-precision wafer stage, vacuum system, imaging system, and a controller which controls various parameters, such as electron beam scanning, focusing and other peripherals. The gun assembly produces the primary electron beam. The electromagnetic lenses and apertures focus the primary beam on the specimen. The vacuum system allows passage of the electron beam through the column without interference from air molecules [1]. The wafer measurement process consists of locating the measurement site on the wafer, correct setting of the electron beam and the actual data acquisition and image or line scan generation. These activities are coordinated by a vendor-specific SEM controller. Various factors, such as electron beam current, vacuum quality, roundness of the electron beam, alignment of the electron column, and positioning of the wafer influence the accuracy of the measurement. In a typical fabrication facility, each SEM has to be fine-tuned individually to assure the same results from different SEMs. This tuning process has to be repeated as necessary, which results in loss of production during the time that the SEM is offline. A system that monitors the vital signs of the measurement system performance and determines the necessary corrective action as well as communicates this status to a supervisory system of the facility will be a significant advancement to the existing state-of-the-art.

A Hitachi cold field emission critical dimension scanning electron microscope (CD-SEM) is being used as a test bed as an exploratory approach to the above mentioned strategic needs to develop the following components:

- Define standardized interface requirements for SEM electron columns. These requirements would be compatible with electron columns from different manufacturers since the designs are all very similar.

- Define a standard methodology to monitor the vacuum system and peripheral devices such as wafer transport systems.

- Develop a standardized operator interface that ties in the above components. Such an interface would have an easy-to-use, high level scripting language for programming automated measurements. It would also have connectivity to networks for data transfer and remote operation.

Specifically, the following system components will be monitored: 1) vacuum system along the column, 2) wafer handling system, and 3) diagnostic signals along the column.

Functional Description of SEM

The Hitachi[1] S-6000 CD-SEM has two separable chambers in the electron optical column. The gun chamber (and the condenser lens) pumped by three ion-getter pumps (IP), while a turbo-molecular pump pumps the specimen chamber. In normal operation, the vacuum pressures are typically 10^{-3} to 10^{-4} Pa in the specimen chamber and the three ion-getter pumps provide excellent, high vacuum conditions of 10^{-6} to 10^{-7} Pa for the cold field emission cathode. A schematic drawing of the sectional view of the column is given in Figure 1. IP_1 is the largest pump at the upper part of the electron gun chamber, IP_2 is pumping the lower part of the electron gun chamber and IP_3 is located at the condenser lens. In order to achieve and maintain a good, clean vacuum, it is recommended to heat

[1] Commercial equipment, instruments, or materials are identified in this report in order to specify adequately certain procedures. In no case, does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

various parts of the gun chamber in a "baking cycle". During this procedure molecules are being released from the inner surfaces of the gun chamber and pumped away (trapped) by the ion-getter pumps. While the chamber is hot, this leads to poorer vacuum values (i.e., higher pressure) but when it cools, the vacuum improves.

By following the vacuum values during the baking cycle, it is possible to find indications of problems with the vacuum system, a small leak for example. In a properly functioning SEM, the pump curves will follow a pattern similar to Figure 2. The minimum required and expected operating conditions for normal operations, before and after the baking cycle, are listed in Table 1.

The wafer handling system is the slowest part of the measurement of individual wafers. A typical throughput with this class of CD-SEM is 20 wafers per hour. The vacuum quality and timing of throughput of the wafer handling system will be monitored also.

OPERATING CONDITIONS	IP_1 (Pa)	IP_2 (Pa)	IP_3 (Pa)
Required minimum	$< 1 \times 10^{-6}$	$< 1 \times 10^{-5}$	$< 5 \times 10^{-4}$
Before bake	$< 1 \times 10^{-7}$	$< 2 \times 10^{-6}$	$< 7 \times 10^{-5}$
After bake	$< 1 \times 10^{-7}$	$< 2 \times 10^{-7}$	$< 5 \times 10^{-6}$

Table 1. Operating conditions for the vacuum pumps

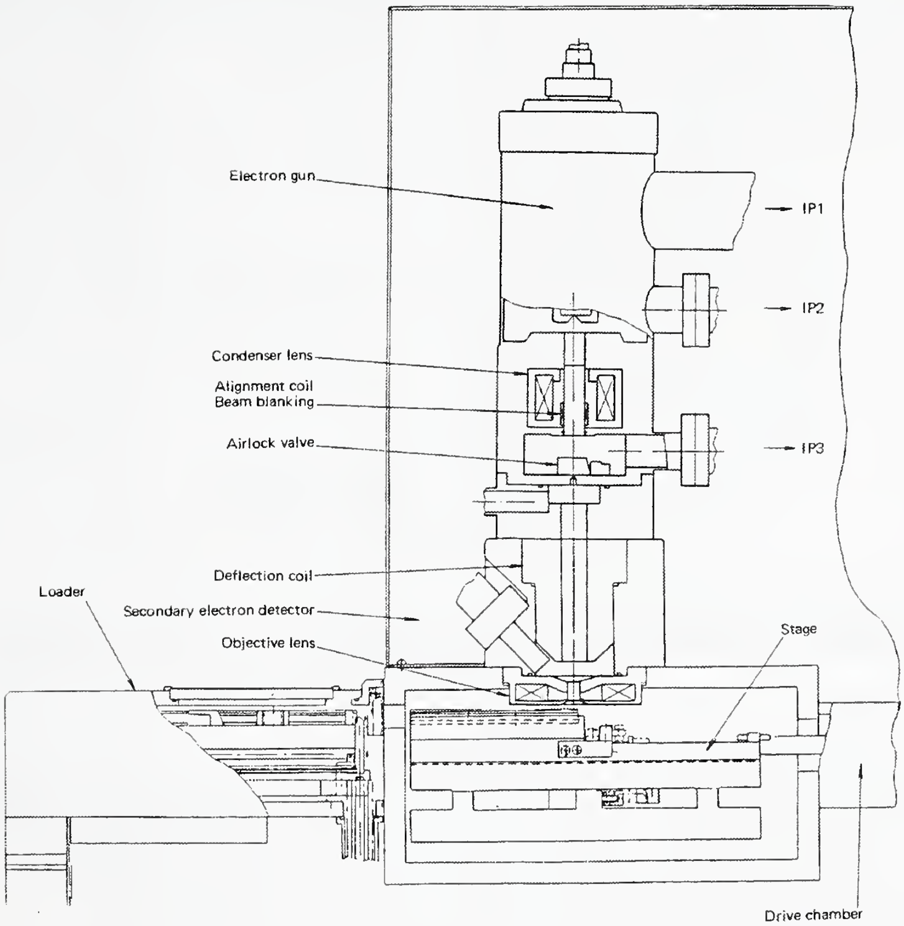


Figure 1. Schematic drawing of the electron optical column

The image quality produced by the SEM correlates with the status of the tuning, i.e., degree of alignment of various components the electron beam column. The emission current is one measure of goodness of the tip, the cathode of the electron gun. Any deviation from the optimal settings due to drift of the electronics or the displacement of the tip results in degradation of image and therefore measurement quality. The possibility of monitoring the effects gives an excellent opportunity for improvement of SEM-based measurements. The next section will summarize the proposed subsystems and signals to be monitored in the SEM Sentinel system by the completion of the first phase of this program.

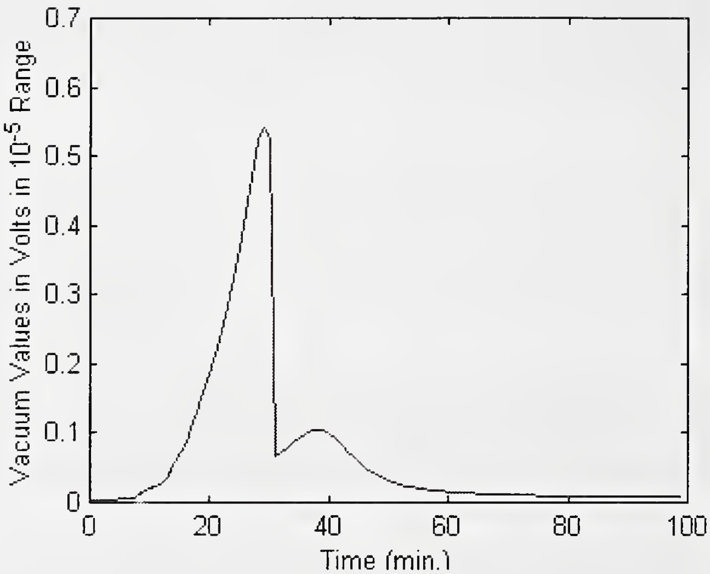


Figure 2. Vacuum change through a baking cycle of a properly functioning gun chamber

Data Acquisition System

The data acquisition system (DAQ) consists of two National Instruments data acquisition boards[2], **Lab**oratory **V**irtual **I**nstrument **E**ngineering **W**orkbench (LabVIEW) graphical programming software, one Data Translation digital I/O board[3], a PC with a Pentium II, 200 MHz processor and 64 MBytes of RAM under Windows 98. Table 2 summarizes the proposed subsystems and signals to be monitored in the SEM Sentinel system by the completion of the first phase of this program. The system is still under development to meet the level of monitoring/diagnostics desired. Additional and/or different signals may be monitored throughout the system, depending on the information learned as the diagnostic system is exercised. Due to low voltage levels and suspected ground-loop problems, the vacuum signals (IP_1, IP_2, IP_3, Pi_1, Pi_2, Pe_1, Pe_2) were monitored in differential mode.

[2] Each board contains 16 analog and 8 digital channels, with 12-bit and 250kSamples/sec capability, PCI-MIO-16E-4.

[3] 32 channels, DT2817.

SYSTEM	SUBSYSTEM	MONITORED SIGNALS
Vacuum	Column	IP_1 - pressure at ion-getter pump 1
		IP_2 - pressure at ion-getter pump 2
		IP_3 - pressure at ion-getter pump 3
	Wafer Handling	Pi_1 - Pirani gauge 1
		Pi_2 - Pirani gauge 2
		Pe_1 - Penning gauge 1
		Pe_2 - Penning gauge 2
Electron Optics	Electron Gun	Emission Current
	Condenser Lens	Focus
		Astigmatism in X
		Astigmatism in Y
	Objective Lens	Focus
		Astigmatism in X
		Astigmatism in Y
	Primary Electron Beam	Current
Wafer Loader	Wafer Transfer Timing	Lid to vacuum chamber open/close switch
		Arm that places wafer to/from loader from/to cassette
		Photoelectric switch that detects the transfer of the wafer to/from loader from/to cassette

Table 2. Summary of Proposed Subsystems and Signals to be Monitored.

NI-DAQ is the driver software for the National Instruments data acquisition hardware. This software includes a utility to configure the hardware and also acts as an interface between the LabVIEW software and the devices. The first of the DAQ hardware boards, designated as Device 1, is configured to be in differential mode. This mode was used due to the noise problems encountered with the signals of the ion-getter pumps, which are less than 1 volt. There are only 8 channels available for this board when configured in differential mode. For the Data Translation digital input/output (DIO) board, drivers were not available to interface with LabVIEW, so a LabVIEW function, which enables direct communication with the board in memory is used. This command, which is available under Windows 95 and 98, is not available with the Windows NT operating system due to the manner in which memory is managed in NT.

An interface was developed to communicate between the data acquisition system and the SEM. The interface includes a board with optical isolation of the signals to/from the SEM. The design of the SEM provided break out points for the ion getter pump signals. However, these signals are voltages that also interface with a meter on the front panel of the SEM. This meter has user-selectable range settings for viewing the various pumps. The five range settings for the vacuum pressure readings are 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, where the units are Pa. An automatic switching system for these settings was implemented through the interface hardware with the DIO board and LabVIEW. The control logic of this automatic switching system is explained in more detail in the Appendix.

LabVIEW is an environment in which programs are developed with graphics. Traditional programming languages (e.g., Pascal, C, etc.) are developed with text. The graphical programming environment, called *G*, relies on graphical symbols rather than a textual language to describe the programming actions. LabVIEW programs are called *virtual instruments* (VIs) because their functionality and appearance usually imitate actual instruments. There are three main parts of a VI: 1) front panel, the interactive user interface 2) block diagram, source code and executable part of the program, (3) subroutines or subVIs [2]. The front panel of the VI for the SEM Sentinel system, at the time of this report, is shown in Figures 3a and 3b. This module allowed for the functionality of datalogging the analog signals for the vacuum system and automatic switching for the gains for the vacuum signals for the ion-getter pumps. The view of the front panel shown in Figure 3a is the desired display during data collection. The analog signals for the vacuum system are plotted on the waveform chart during data collection. The data is saved in a spreadsheet file format (ASCII with tabs and linefeed/carriage returns). The user may select the following from this view of the front panel: 1) digits of precision for the saved data, 2) the minimum time delay between each saved set of data, 3) channel headers for the legend and the saved file, and (4) the initial gain for the ion-getter pump display (for this setting to be effective, the switches on the interface board must be switched away from the "Manual" position). The view of the front panel shown in Figure 3b contains more of the lower-level settings that the user usually leaves constant. Shown in this view of the panel are the following. 1) Selection of the device, a board configured with NI-DAQ; 2) The channels used. For device 1, 7 of the 8 channels are used for this example; 3) Input limits each channel. This transparently adjusts the gain of each channel for good fidelity of the incoming signal; 4) Scan rate of the device. The maximum scan rate for the PCI-MIO-16-E4 is 250 ksamples/sec. In this example, the board is scanning at 3000 samples/sec; 5) Number of points to average for each recorded data point. The ion-getter pump signals IP_1 and IP_2 were noisy and therefore an average of 1000 points is made for each recorded data point. Any errors for device 1 will be displayed in the "error out" section.

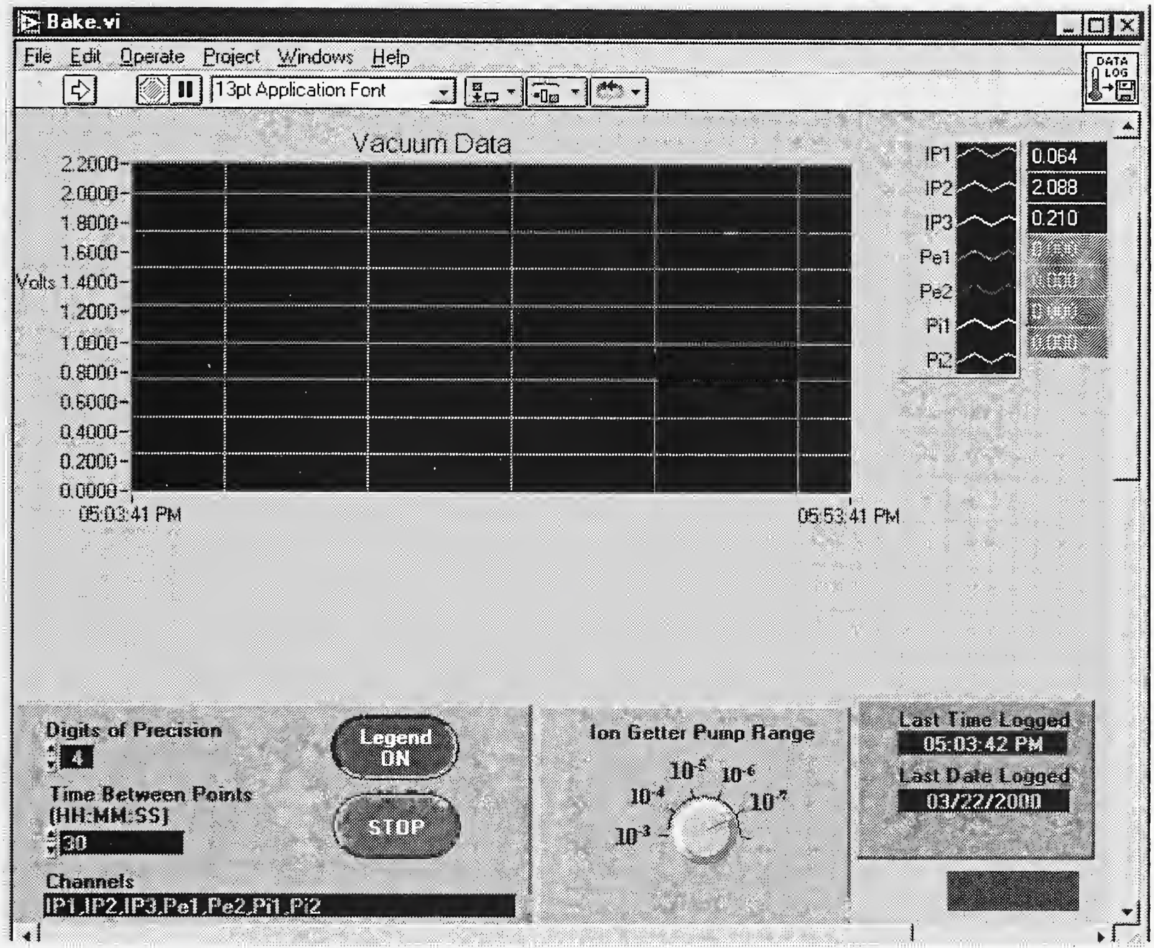


Figure 3a. Front panel view of the SEM Sentinel program.

A partial view of the source code of the SEM Sentinel program, is shown in Figure 4. This program is a compilation of various examples (data logger, DAQ, etc.) given with LabVIEW as well as added functions required for this application.

Another module was developed to specifically monitor the timing signals and the vacuum system responses during wafer loading and unloading of the wafer handling subsystem. The front panel of this module is shown in Figure 5. Two waveform graphs are present in the front panel. The top graph displays the signals associated with the vacuum gauges and is configured with a semi-log scale. The bottom graph displays the timing of the loading and unloading of the wafer. The sluggish response curves of the vacuum systems indicate a small leak.

A more detailed explanation of the source code of the software developed at the time of this report is found in the Appendix.

The data collected with the SEM Sentinel may be displayed with a modified example from LabVIEW. The viewer is shown if Figure 6. The user runs the VI and is prompted for the desired data file, start date, start time, and number of points desired to plot.

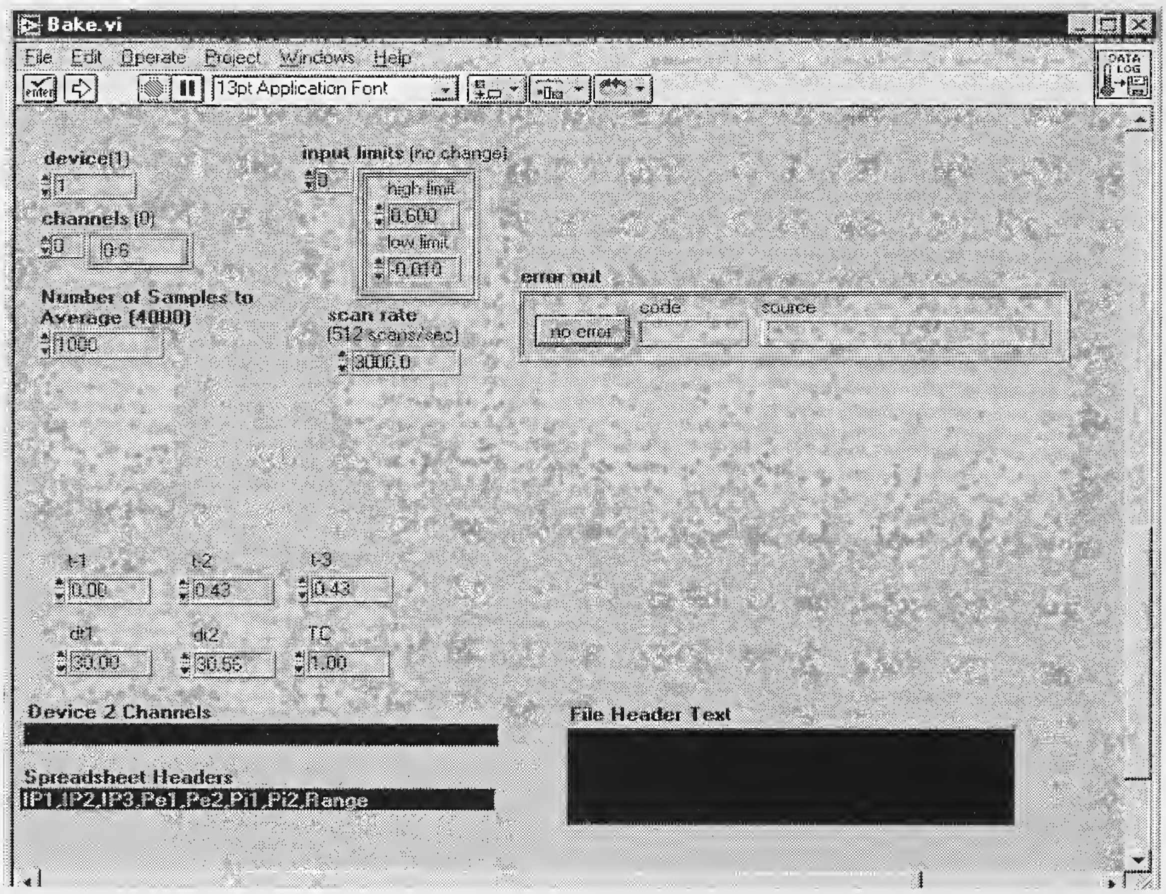


Figure 3b. View two of the front panel of the SEM Sentinel system.

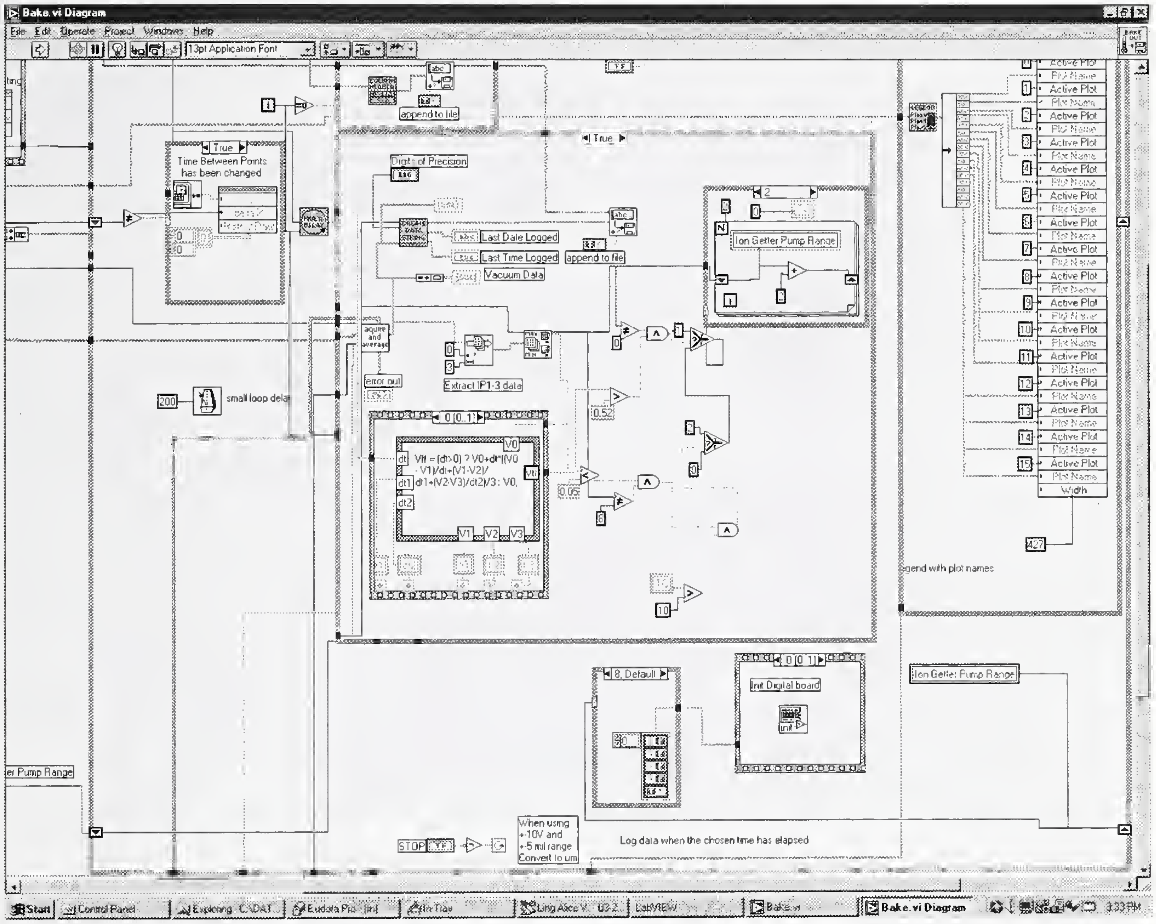
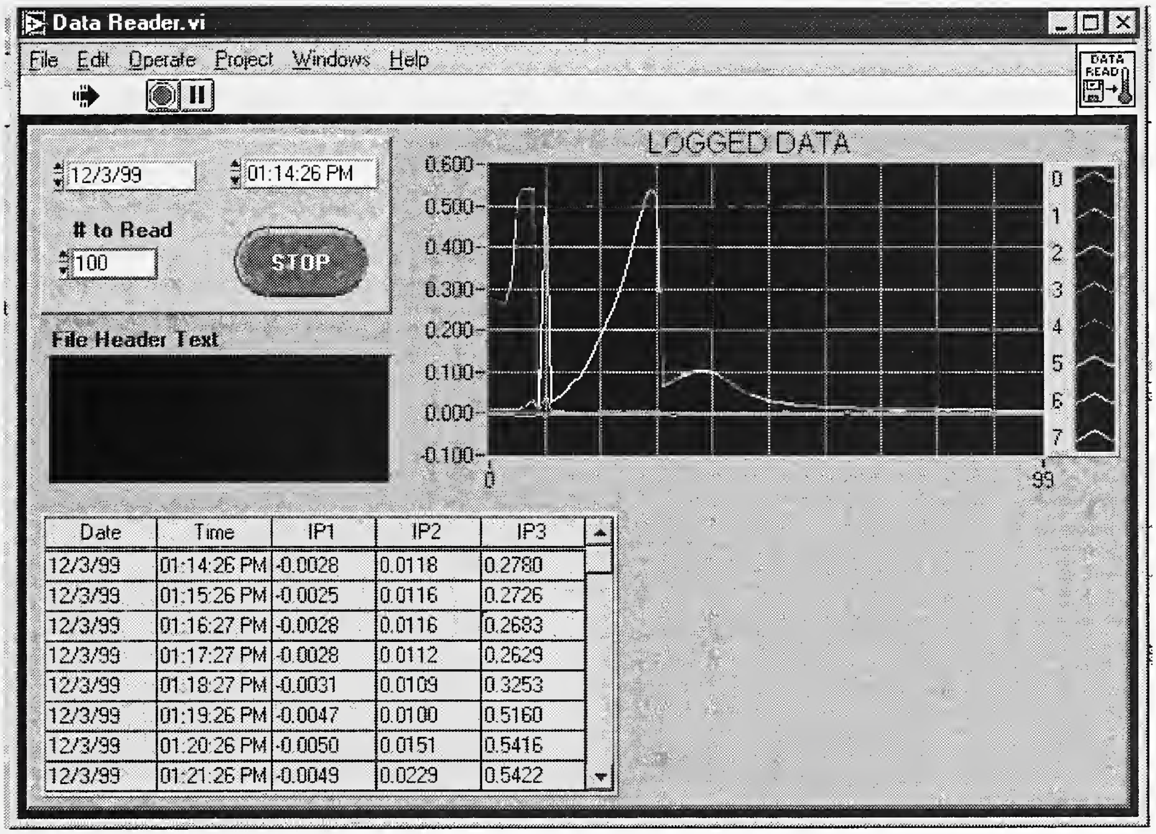


Figure 4. Partial View of the Source Code of the SEM Sentinel system.

Figure 5. Module Developed for Monitoring the Wafer Handling Subsystem.



Date	Time	IP1	IP2	IP3
12/3/99	01:14:26 PM	-0.0028	0.0118	0.2780
12/3/99	01:15:26 PM	-0.0025	0.0116	0.2726
12/3/99	01:16:27 PM	-0.0028	0.0116	0.2683
12/3/99	01:17:27 PM	-0.0028	0.0112	0.2629
12/3/99	01:18:27 PM	-0.0031	0.0109	0.3253
12/3/99	01:19:26 PM	-0.0047	0.0100	0.5160
12/3/99	01:20:26 PM	-0.0050	0.0151	0.5416
12/3/99	01:21:26 PM	-0.0049	0.0229	0.5422

Figure 6. Data Reader program used to display the logged data.

Experiments

The experiments described in this section were made prior to the implementation of automatic switching of the ion-getter pump gains. A data acquisition system was configured to collect voltage readings corresponding to the pressure for the three ion-getter pumps, IP_1, IP_2 and IP_3. Data was collected for an entire baking cycle, around 18.5 hours. Voltages of the three vacuum pumps are plotted with a semi-log scale for the entire baking cycle in Figure 7. The semi-log plot enables a clearer detection of phenomena occurring during the test. All three ion-getter pump signals are shown since they were monitored for the test. However, the most interesting of the three curves is IP_3.

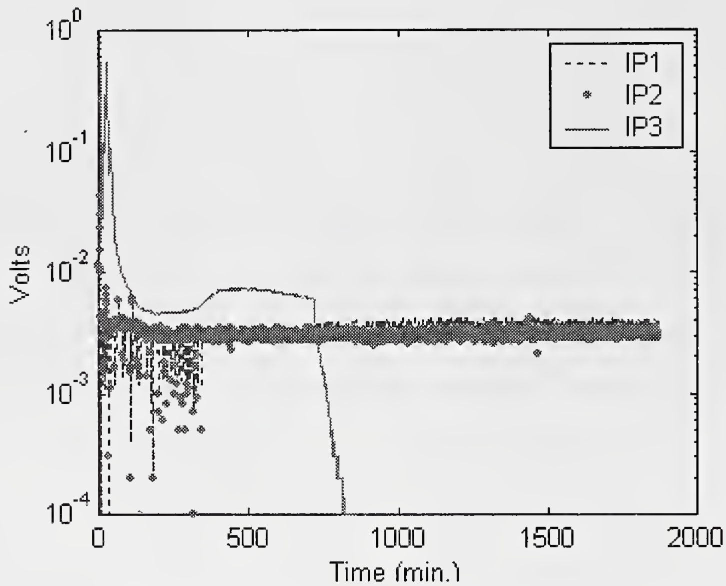


Figure 7. Semi-log Plot for the Entire Bake Test.

With this experimental setup, it appears that most of the activity is seen at pump IP_3, during two different time periods: (1) the first 100 minutes, and (2) between about 350 and 700 minutes. Access to the voltage signals for IP_1, IP_2, and IP_3, were conveniently provided by the manufacturer as connections in the back of the ion-getter pump power supply. Unfortunately, the circuit providing the IP signals require the user to manually switch the gain, which provide signals corresponding to vacuum pressure in 10^{-4} to 10^{-7} Pascal range. There are three different gain settings used throughout the first experiment. In Figure 8, during the first 9 minutes the setting was set to the 10^{-7} Pa range, the next two minutes at the 10^{-6} Pa range, and for the remainder of the experiment, at the 10^{-5} Pa range. The first two peaks at ~0.53 Volts, correspond to switching the gain and the resulting signal level changes. The significant features to note in this figure are the duration of time necessary to reach the final (large) peak (30 minutes) and the shape of the tail of the last (small) peak in the first heating cycle, which is smoothly decaying (normal) as opposed to a sharp drop (abnormal). The rise in pressure only lasting 30 minutes is also a sign that the vacuum system is functioning as expected. In Figure 9, a last small peak indicates an out-gassing of molecules in a second part of the heating cycle.

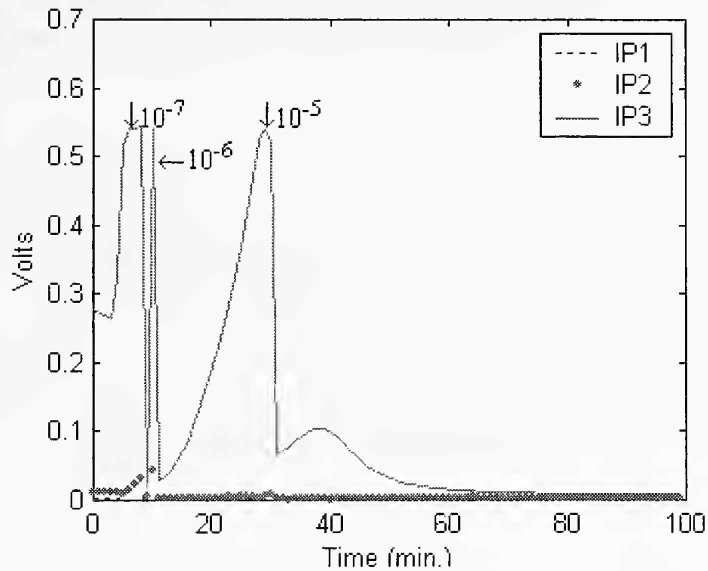


Figure 8. First 100 minutes of the baking cycle

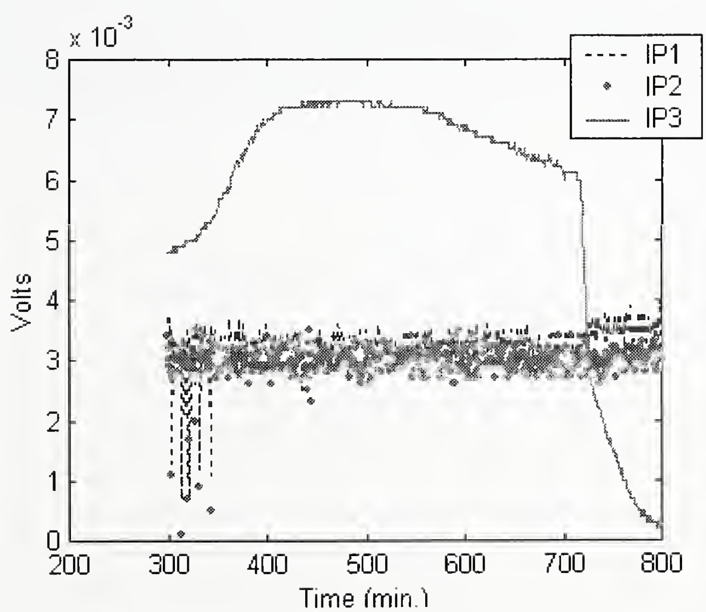


Figure 9. Second part of the baking cycle to remove remaining molecules.

The second baking experiment was performed only 5 days after the first. Therefore, the column was cleaner and there were fewer molecules to pump out, only requiring one gain change from 10^{-7} Pa to 10^{-6} Pa at the first peak. The resulting vacuum pressure curves also varied from the first test. The entire baking cycle for the second test is shown in Figure 10. The gain was switched back to 10^{-7} Pa range at the end of the experiment, causing the jump at the end.

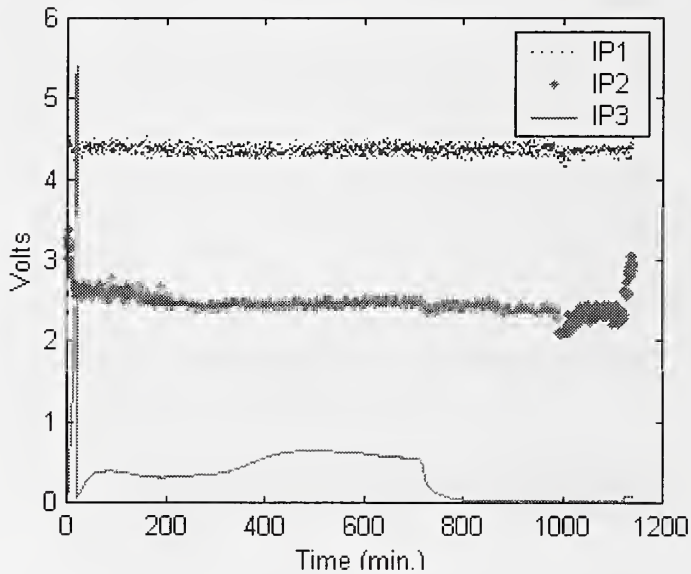


Figure 10. Baking cycle for the second test

Summary

The system described in this report is Phase I_a. Phase I_b will include 1) the implementation of a second DAQ board for collection of signals along the beam column and 2) timing of the wafer handling system and monitoring of vacuum levels during wafer transfer. Phase I allows for full monitoring of important parameters of the SEM, but the systems run with original controls. In this sense the SEM Sentinel system is a passive system.

Future efforts include the addition of image capture from the SEM and control of various signals along the beam column. The SEM Sentinel system after finishing the second phase will be active, because several SEM parameters will be controlled as well as monitored. This will allow the user to ensure continuous and much better measurement quality, given that it is feasible to correlate image quality with the state of the various settings of the electron beam column parameters. In the future, this system can be directly applied to many types of SEMs and other measurement instrumentation.

References

[1] Postek, M. T., Howard, K. S., Johnson, A.H., McMichael, K.L., Scanning Electron Microscopy, A Student's Handbook, 1980, Michael T. Postek, Jr. and Ladd Research Industries, Inc.

[2] Wells, L. K., Travis, J., LabVIEW for Everyone, Graphical Programming Made Even Easier, 1997, Prentice-Hall, PTR

Appendix

Explanation of the Source Code for the SEM Sentinel System

Two modules and their sub VIs will be covered in this Appendix: Bake.vi and Wafer.vi. There aren't major differences between the two VIs. The default parameters for Bake.vi are set for a slower process, i.e., the bake out process, where the data is saved every 30 seconds. The default parameters for Wafer.vi are set to monitor a faster process, i.e., the wafer handling system, where the data is saved every second. All of the VIs and their associated sub VIs are located in a library file named V16Ea.llb.

Bake.vi

Most of the source code for Bake.vi is shown in Figure 4 in the main section of this report. The examples used to assemble the major portion of Bake.vi are taken from the "Data Logger to Spreadsheet File.vi" located in c:\Program Files\National Instruments\LabVIEW\examples\daq\solution\datalog.llb library and the "SCXI-1122 Voltage.vi" located in c:\Program Files\National Instruments\LabVIEW\examples\daq\scxi\scxi_ai.llb library. Figure A1 shows the hierarchy of the 'Bake.vi' module. The sub VIs will be described in the order they are listed in Figure A1.

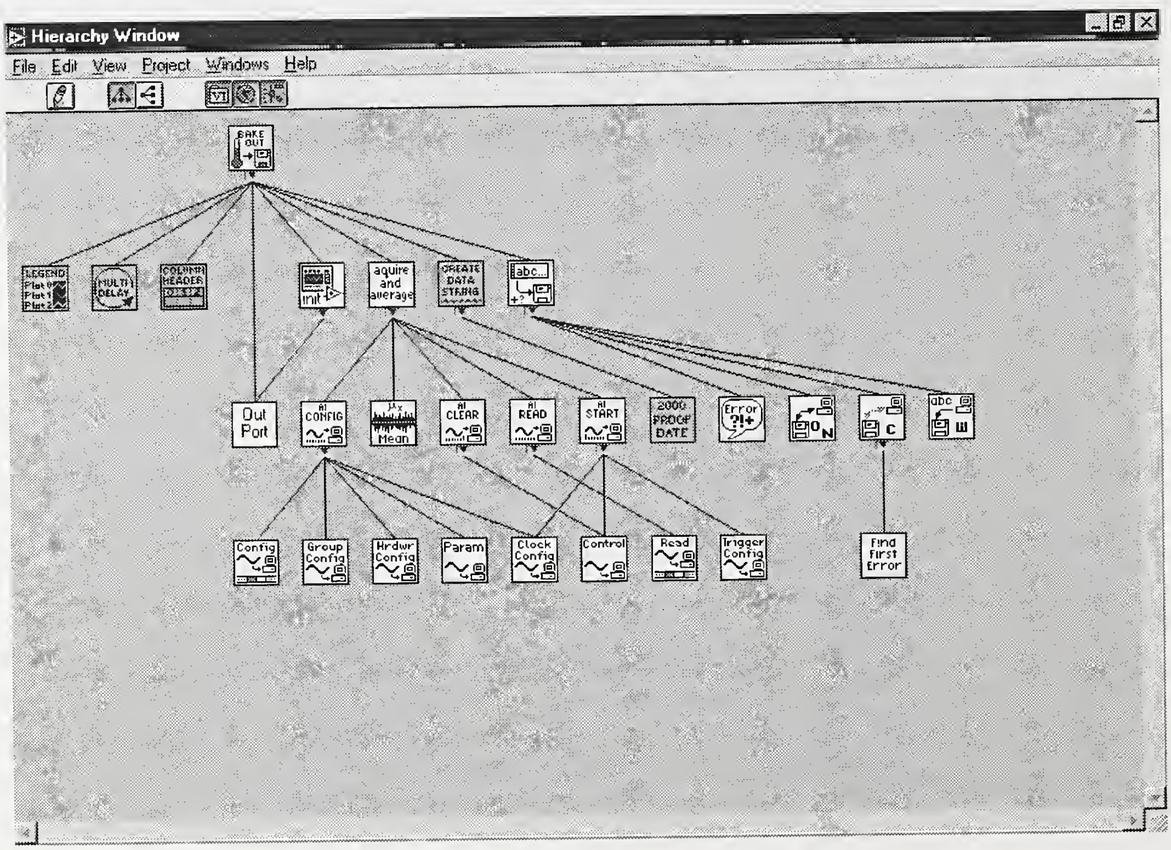


Figure A1. Hierarchy of SubVIs Called From Bake.vi.

A *while* loop encloses most of the functions (except for constants that don't change during the execution of the program). The loop terminates when the user presses the "Stop" button, either on the front panel or along the top menu (the red button next to the right arrow). After the user starts the VI and before the *while* loop starts, the user is prompted for the file name for the storage of the data. This module currently does not enable appending to existing logged files. The user will be warned prior to overwriting an existing file. During the first iteration of the *while* loop, a header containing the list from the "Channels" user input is written to the file.

1) The "Legend" icon contains the subroutine named "channel string to name array 15.vi", which is a slightly modified version obtained from the datalogger example. This sub VI strips the commas out of a string that the user provides on the front panel to label desired channel names on the legend of the graph. The Bake.vi program takes the output of this sub VI (data contained in a cluster), unbundles the cluster into its individual components, and feeds the channel names to the specified attributes of the graph.
2) The "Multi Delay" icon contains the subroutine named "multiple time delay match b.vi". The source code is shown in Figure A2. This subroutine compares the current time with the last time data was saved. When this difference is greater than the "Time Between Points (HH:MM:SS)" user input, then the case statement activating the data collection is enabled. This also outputs the actual time since the last dataset was saved. For the first iteration, this number is simply the nominal time difference given by the user. The output of the 'Multi Delay' function feeds into a *case statement* that tests whether or not to acquire and save data.
3) The "Column Header" icon contains the subroutine named "string column header 1.vi". This sub VI places the header in the data file by concatenating the "Date" and "Time" strings to the "Spreadsheet Headers" character string which the user has input. The current default string in the "Spreadsheet Headers" variable is "IP1,IP2,IP3,Pe1,Pe2,Pi1,Pi2,Range".
4) The "init" icon contains the DT_INIT.vi which initializes the Data Translation DIO board to "read" at ports 0 and 1, and "write" at ports 2 and 3. This VI is placed in a sequence structure, where the board initializes prior to any read or write to the DIO board. The "Out Port" sub VI writes data directly to memory locations of the DIO board. The NT operating system will not support this function due to the manner in which NT manages memory. Data Translation does not have a 32-bit driver to support this board in NT.
5) The "Acquire and Average.vi" is the sub VI which handles the acquiring and averaging of data from the A/D boards. This sub vi is passed parameters from Bake.vi such as: (1) device, (2) channels, (3) scan rate, (4) number of samples to average, (5) input limits of each channel, (6) any errors which may have occurred. This sub VI will first check if there are any incoming errors. If there are errors, the VI will not execute. If no errors, then the following analog input sub VIs will execute.
   a) AI CONFIG configures the hardware and allocates a buffer for the given device. The following are low level sub VIs associated with this sub VI.

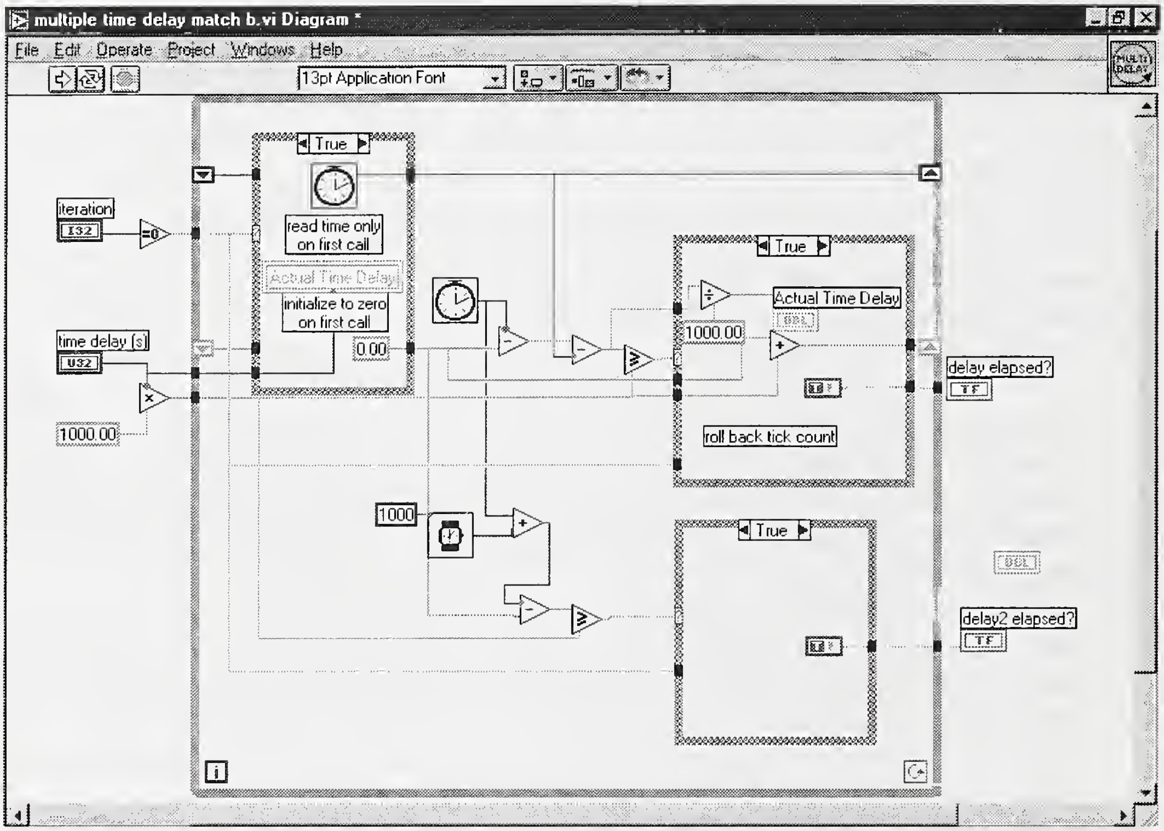


Figure A2. Source Code for Comparing Current Time with Desired Delay Between Saved Samples.

i) The "Config" icon contains the "AI Buffer Config.vi", which allocates memory to store analog input data until the "AI Buffer Read.vi" can deliver it.
ii) The "Group Config" icon contains the "AI Group Config.vi", which defines and assigns what channels belong to a group.
iii) The "Hrdwre Config" icon contains the "AI Hardware Config.vi", which configures either the upper and lower input limits or the range, polarity, and gain.
iv) The "Param" icon contains the "AI Parameter.vi", which configures and retrieves miscellaneous parameters associated with Analog Input operation of a device that are not covered with other AI VIs.
v) The "Clock Config" icon contains the "AI Clock Config.vi", which sets the channel and scan clock rates.

b) The "MEAN" sub VI is associated with the computation of the average of the data samples per channel.
c) The "AI Clear" sub VI uses the "AI Control.vi" to stop an acquisition associated with a particular task ID and release associated internal resources, including buffers.
d) The "AI READ" sub VI calls the "AI Buffer Read.vi" to read data from a buffered analog input acquisition.
e) AI START starts an analog input operation, sets the scan rate and trigger condition and then starts an acquisition. This VI calls the following advanced analog input VIs to start the buffered analog input acquisition.

i) "AI Clock Config.vi" configures the acquisition for the specified scan clock source and the specified scan rate.

ii) "AI Trigger Config.vi" sets a trigger according to trigger type.

iii) "AI Control.vi" starts the acquisition, using total scans, pretrigger scans, and number of buffers to acquire to determine how much data to acquire.

6) The "Create Data String" icon contains the "Create Data Stringb.vi", which takes the time, date, range of the ion-getter pump and acquired analog data and formats the file to be spreadsheet readable (i.e., an ASCII file with tabs and linefeed carriage returns). The mapping of the recorded and actual numeric ranges for the ion-getter pump gain is given in Table A1. The binary values which are written to the digital IO board for each range are also given in Table A1 (more detail about switching to come). This sub VI calls the "get 2000 proof datetime 1.vi" to get the date and time to log the data.

RECORDED RANGE	ACTUAL RANGE	BINARY VALUES WRITTEN TO DIO
8	10^{-7}	10000
6	10^{-6}	01000
4	10^{-4}	00100
2	10^{-4}	00010
0	10^{-3}	00001

Table A1. Mapping of Recorded to Actual Range of Ion Getter Pump Gain.

7) The "Write Characters to File.vi" icon is contained in three places in "Bake.vi". First prior to the start of the while loop to open the datafile and write a user designated header into the file. Second, at the first iteration of the while loop to write the header to the spreadsheet file. Third, will append character string containing the collected data to the data file. This sub vi will call sub VIs for (i) general error handling, (ii) Open/Create/Replace files, (iii) closing the file, and (iv) writing data to the file.

The logic for the automatic switching of gain ranges for the ion-getter pumps is described in this section. The *case statement*, which is 'True' when the user-designated time delay The "Array Subset.vi", shown in Figure A3a, extracts a subset from the data array. In this example, the ion-getter pump data, IP1-3 is physically connected on channels 0-2 of the data acquisition board. The desired channels are input by the user on the front panel, Figure A3b. From Figure A3a, a subset of data starting at the 0^{th} array element with length 3 is desired, which is the data for IP1-3. The maximum value of data from IP1-3, *V0*, is used as an input to the formula node shown in Figure A4. The equation contained in the formula node will predict the maximum voltage value for IP1-3 for the next time step. The actual time between the last data "acquire and save", *dt*, is calculated by the "Multi Delay" sub vi and is another input to the formula. The previous two values for *dt*, *dt1* and *dt2*, are also inputs to the formula. The previous three values for *V0*, (e.g., *V1*, *V2*, and *V3*) are also inputs to the formula. The actual equation in the formula node is

Vff = (dt>0) ? V0+dt((V0 - V1)/dt+(V1-V2)/dt1+(V2-V3)/dt2)/3 : V0;*

where *(dt>0) ?* is a statement which means that if *dt* is greater than 0, then *Vff* is equal to the first expression *V0+dt*((V0 - V1)/dt+(V1-V2)/dt1+(V2-V3)/dt2)/3*, the predicted value of the maximum voltage at the next time step. If *dt* is not greater than zero, then *Vff* is equal to the current maximum voltage, *V0*.

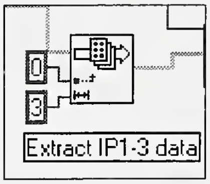


Figure A3a. Array Subset vi.

Figure A3b. Channel Input on Front Panel.

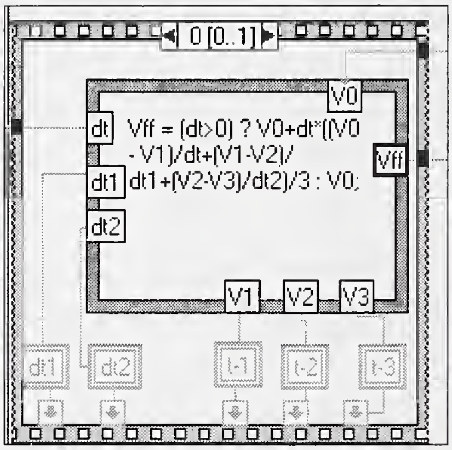


Figure A4. Formula Node Used to Predict the Voltage at the Next Time Step.

The variable for the time constant, *TC*, is set to zero when a switch, up or down, is made. Each time data is acquired and saved is considered one time constant. The criteria used to switch up the range is: IF *Vff* is greater than 0.45 volts, TC is greater than 2, and the range is not at the maximum range, 10^{-3}, which is represented as 0 (see Table A1), then switch the range up. This is accomplished by subtracting 2 from the variable, "Ion Getter Pump Range", where the values range from 0 to 8 as seen in Table A1. The case which switches up the "Ion Getter Pump Range" is shown in Figure A5. This case uses a *for loop* with 2 iterations to subtract 2 from the variable "Ion Getter Pump Range", which is a "write local" variable. The criteria to switch down the range is: IF *Vff* is less than 0.001 volts, and the range is not at the minimum range, 10^{-7}, which is represented as 8, and the time constant, *TC* is greater than 10, then switch down. The time constant is used as a criteria to give the system time to respond to the higher gain range; to prevent an oscillatory switching between gain ranges. The thresholds for *Vff* and other aspect of the switching criteria may have to be tuned as more experiments are performed. Once the variable "Ion Getter Pump Range" is changed, then another case statement writes the proper value to the digital IO board. Figure A6 shows the default case 8, range 10^{-7}, which writes the binary value 10000 to the proper memory location. The binary values written to the DIO board for each range are given in Table A1.

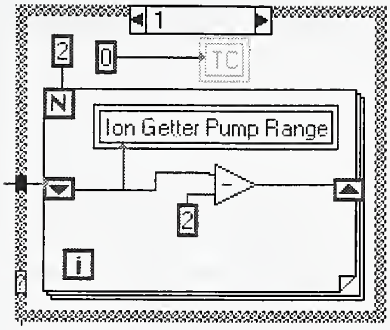


Figure A5. Case #1, Which Switches to a Higher Range.

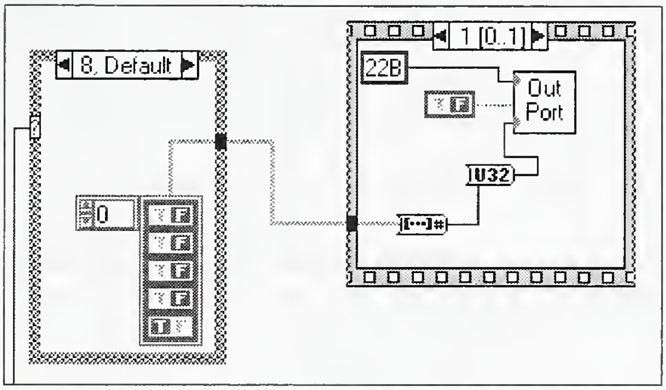


Figure A6. Writing the Binary Value to Represent the 10^{-7} Range to the Memory for the DIO Board.

Wafer.vi

Figures A7a and A7b show most of the source code of the two independent while loops that run during the execution of Wafer.vi. The source code for the first while loop, mostly captured in Figure A7a, is very similar to the functionality of Bake.vi. The source code for the second while loop, mostly captured in Figure A7b, is a modification of the example "Count Time-Int (DAQ-STC).vi" located in c:\Program Files\National Instruments\LabVIEW\examples\daq\counter\daq-stc.llb. Figure A8 shows the hierarchy of the 'Wafer.vi' module. The sub VIs which are not described for Bake.vi will be described in the order they are listed in Figure A8.

1) "Counter Read.vi" - calls CTR Control to read the counter or counters identified by task ID. Each VI is designed to read one counter of a DAQ-STC counter chip. There are two counter chips on each of the DAQ boards. Three timers are currently used in this application to detect the open/close of switches located at the following locations: (1) lid of the loader chamber, (2) wafer transfer arm, and (3) photoelectric sensor. The output of each switch, a TTL signal, is connected to the input of the gate of each timer. The current settings are to count while the gate signal is high for (1) lid and (2) arm, and count while gate signal is low for (3) photoelectric sensor.
    a) "CTR Control.vi" - controls and reads groups of counters. Control operations include starting, stopping, and setting the output state.
2) " Counter Start.vi" - starts the counters identified by task ID.

3) "Counter Stop.vi" - calls CTR Control conditionally to stop a count operation on an input error or immediately.
4) "Event or Time Counter Config.vi" - configures one or two counters to count the signal on the specified counter's SOURCE pin or the number of cycles of a specified internal timebase signal.
   a) "CTR Group Config.vi" - collects one or more counters into a group. Counter groups containing more than one counter are useful for starting, stopping, or reading multiple counters simultaneously. Groups with multiple counters are not currently supported by our A/D hardware (MIO-E Series boards).
   b) "Adjacent Counters.vi" - identifies the counters logically adjacent to a specified counter of an MIO or TIO board. It also returns the counter size (number of bits) and its timebases. Boards with the DAQ-STC have two 24-bit counters (0 and 1). Many counter operations require two or more counters, and in some cases, you can use a logically adjacent counter without external wiring. The Adjacent Counters VI lets you build VIs that have only one counter parameter; the VI is then used to select the other.
      i) "Get DAQ Device Information.vi" - returns configuration information about our device.
   c) "CTR Mode Config.vi" - configures one or more counters for the type of counter operation you want to perform and selects the source signal, gating mode, and output behavior on terminal count.

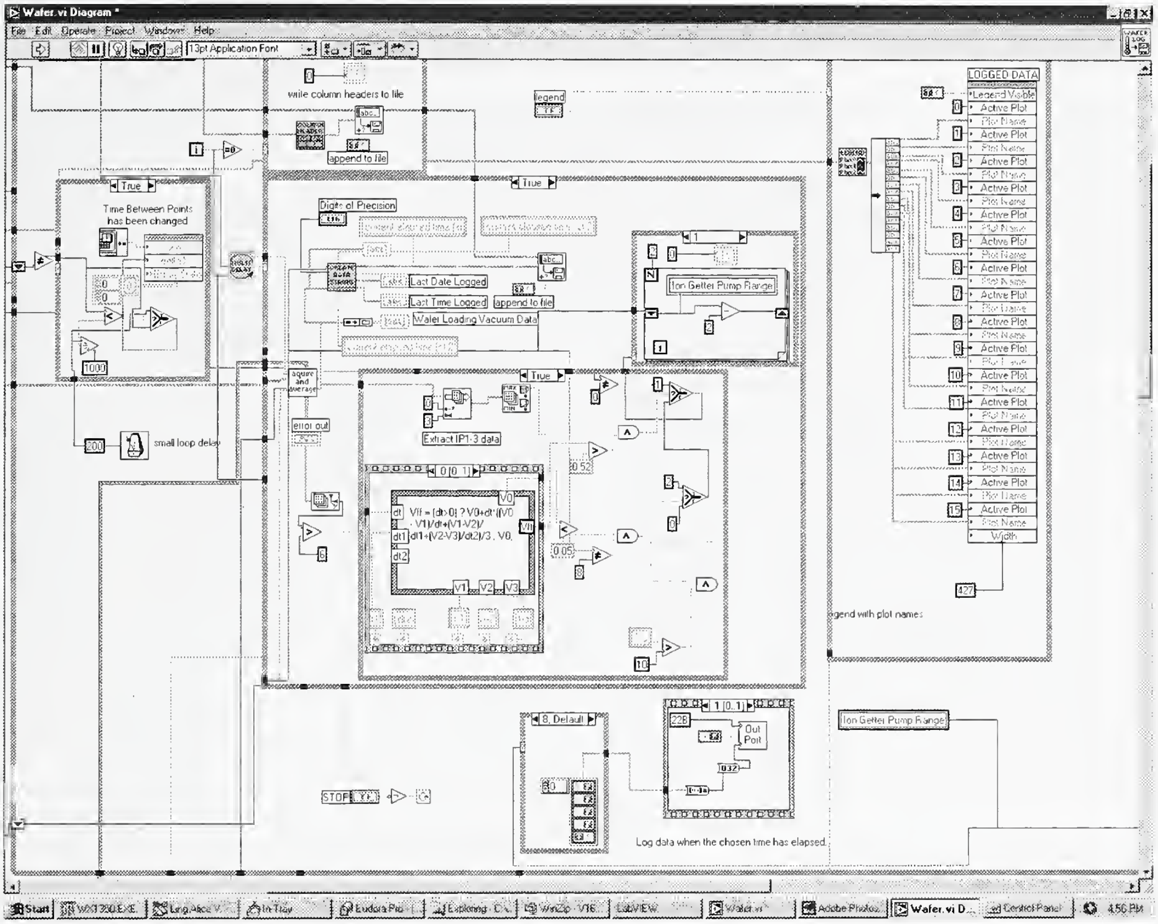


Figure A7a. Source Code of While Loop Containing Data Acquisition and Logging in Wafer.vi.

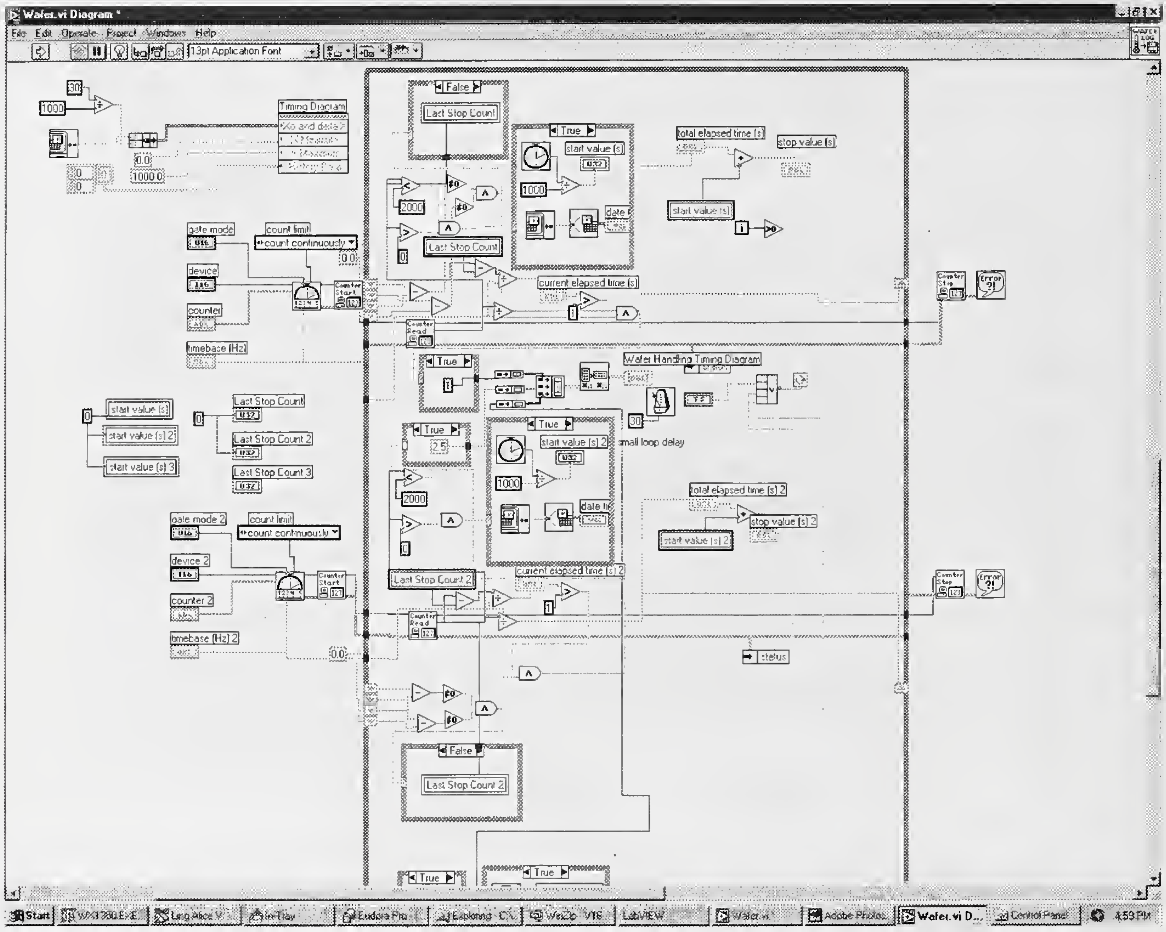


Figure A7b. Source Code for Timing Events Using the Counter Chip on the A/D Board.

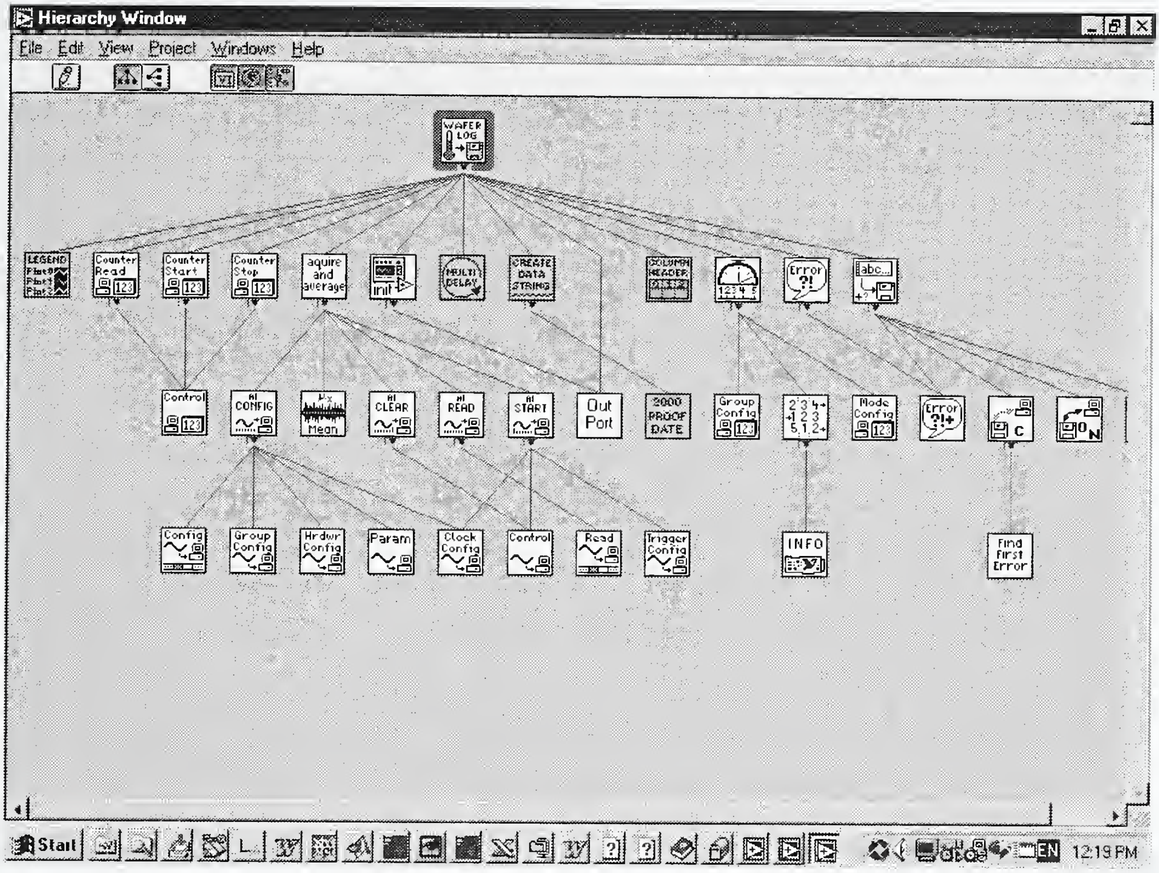


Figure A8. Sub VI Hierarchy for Wafer.vi